Sun-Fi: Architecting Glass for Sunlight Data Transmission

Sahar Ammar, Osama Amin, Mohamed-Slim Alouini and Basem Shihada

***Abstract*—Solar energy, as a sustainable power resource, has mainly been used for electricity generation and heating purposes. Nevertheless, large amounts of daylight are underutilized and primarily used for indoor lighting. In this article, we investigate exploiting sunlight as a green information carrier by passively modulating its power to stream data. Switchable glass technologies can be employed to manipulate the ambient light allowing optical wireless communications. In this context, we explore candidate smart-glass technologies and give an overview of the sunlight modulation communication system, called Sun-Fi.Then, based on the liquid crystal devices technology, we discuss the newly proposed architecture known as dual-cell liquid crystal shutters (DLS), which can establish a flicker-free communication link. Afterward, we stack the DLS elements in an array form while adopting polarization-based modulation and time division multiplexing to modulate the sunlight and transmit the required data. Finally, we define several open issues of the sunlight communication system and provide potential solutions.**

***Index Terms*—Sunlight communication, passive communication, liquid crystal devices (LCDs), time division multiplexing, polarization modulation.**

I. INTRODUCTION

The tremendous rapid growth of wireless communication networks and services increased the spectrum demand and energy requirement. The optical band is receiving increased interest for several merits, such as the plenty of spectrum bandwidth and the free electromagnetic interference. Nevertheless, the optical band is still not well exploited due to its hardware limitations, high-energy requirements of active light sources, and interference impact of ambient light sources. Hence, it is necessary to develop innovative energy-efficient optical wireless communication (OWC) solutions to exploit this rich band [1].

Sunlight communication is a recently proposed technology that modulates underexploited daylight for data transmission via an unlicensed wide optical band. Moreover, it assists in energy conservation by minimizing the utilization of other light sources during daytime and operating by the harvested sunlight energy, which provides a new green communication alternative. Furthermore, adopting this promising technology reduces the optical interference levels in the indoor environment. Nonetheless, manipulating sunlight is a tricky task since it is emitted by the sun, which is an uncontrollable light source. Switchable glass or smart-glass technologies could offer a solution to this problem by appropriately modulating the incident sun rays [2].

Switchable glass is a technology that can be integrated in surfaces such as windows to control the light intensity by applying a specific voltage [3], [4]. It is typically used for several everyday purposes such as daylight shading and sunlight beam steering. There are two operating states for this smart glass known as: a clear state and a dark state, which present the maximum and the minimum light transmission, respectively. The switching time, defined as the time required to switch between the two states, is the most critical characteristic of smart-glass devices in the context of wireless communication applications, because it is proportional to the achievable data rate [5]. The contrast is also another important feature, where it indicates the light transmittance difference between the clear and the dark states, which affects the system's error probability and the link range. Two main categories of smart glass can be distinguished namely electrolyte-based devices and micro-electro-mechanical systems (MEMS)-based Micro-shutters. Liquid crystal devices (LCDs), electrochromic devices (ECDs), and suspended particle devices (SPDs) are included in the first category. Switchable glass technologies are not typically employed for wireless communication, thus it is important to understand its feature as summarized in Table I. Particularly, ECDs and SPDs have long switching times and poor contrast, which makes them inadequate for such application [6]. Although MEMS-based micro-shutters present promising characteristics in terms of switching times and contrast, they can be energy-consuming [7]. On the other hand, LCDs technology is currently a good candidate for the target application, where it offers high contrast, low energy consumption and short switching times [8].

In this paper, we give a general overview on sunlight communication systems. Also, we introduce our novel smart-glass design, known as dual-cell liquid crystal shutter (DLS). Then, we propose Sun-Fi architecture using a passive OWC array of DLS elements that modulate the sunlight by leveraging the LCDs properties. Finally, we discuss the challenges of sunlight communications and presents potential solutions.

The rest of this paper is organized as follows, Section II introduces the sunlight communication concept. Section III describes the DLS design as a smart-glass technology and the proposed sunlight communication system. Section IV discusses open research directions followed by the paper conclusion in Section V.

II. SUNLIGHT COMMUNICATIONS

Sunlight communications falls under the umbrella of passive OWC systems, where there is no control over the light source. In this section, we start by givng a general overview on

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Smart Glass Technology	Switching Time	Contrast	Size	Power Consumption
Liquid Crystal Devices (LCDs) [3], [6], [8]	Short (tens of μs)	High	Small	Low
Electrochromic Devices (ECDs) [3], [6]	Long (few ms)	Low	Small	Low
Suspended Particle Devices (SPDs) [3], [6]	Very Long (few s)	Medium	Large	High
MEMS-based micro-shutters [4], [7]	Short (tens of μs)	High	Very Small	High

TABLE I: Comparison between Smart Glass Technologies.

sunlight communication systems. Then, we summarize the efforts carried out in passive OWC including sunlight and backscatter communication systems.

A. *Sunlight Communication System*

A passive OWC system is composed of three main components including a passive light source, transmissive or reflective surfaces and a receiver. Fig.1 shows a general overview of the sunlight communication system whose operation principle is based on light modulation. The sunlight propagates from the outdoor environment through the glass window, embedded with smart glass elements. These elements modulate the incoming light by modifying its properties such as intensity and polarization. Then, the sunlight travels across the indoor wireless channel reaching the receiver, which typically consists of photodetectors.

B. *Related Works*

Recently, some efforts have been dedicated to develop practical systems that use LCDs to modulate light either for backscatter communications [9]–[12] or sunlight communications [5], [13], [14].

Using retro-reflective fabric, backscatter communication was mainly investigated in [9]–[12]. RetroVLC [11] and PassiveVLC [10] design bi-directional VLC systems employing two different coding and modulation techniques. The light emitted by a LED lamp for the downlink, is backscattered by a retro-reflector and modulated via an LCD shutter to create the passive uplink achieving data rates of 0.5 $Kbps$ and 1 $Kbps$, respectively over distances of 2.4 m and 2 m. In addition, authors of [12] proposed a bi-directional backscatter VLC system for infrastructure-to-vehicle communications. The system employs polarization-based differential reception and complementary optical signaling using two paired photodiodes at the receiver and it present a data rate of 1 $Kbps$ for a link range of 80 m. Moreover, using Polarization-based Quadrature Amplitude Modulation (PQAM) and the delayed superimposition modulation, RetroTurbo utilizes the polarization and time dimensions to establish a backscatter VLC link with an array of 64 LCDs [9]. An equalizer with channel training algorithm is used by the system to reduce the inter-symbol interference (ISI) that has been generated by the modulation technique. RetroTurbo offers the highest data rate among state-of-the-art systems with 8 $Kbps$ realized over a 7.5 m distance.

Furthermore, with 4 to 6 stacked cells used to construct a single pixel transmitter, the designers of the latest sunlight communication system, ChromaLux, demonstrate a transient state of LCDs which provides shorter switching times [13]. By employing a three-level polarization-based method that exploits of the transient state, ChromaLux is capable of transmitting data at a rate of 1 Kbps over long distances reaching up to 50 m. Luxlink [5] is another sunlight communication system that operates over extended ranges (65 m). The authors propose a frequency-based modulation to mitigate the flickering problem, however, the system presents a low data rate of 80 bps, utilizing one LCD pixel and an energy-saving phototransistor. Additionally, PIXEL develops a Visible Light Positioning system using a sunlight communication link [14]. The system employs color shift keying and polarization-based modulation to transmit data over a distance of 10 m at a very low rate of 14 bps. Lastly, in [15], the optical components for a free-space solar communication system, including liquid crystal films and a corner cube retroreflector, are fabricated and used in transmission tests, demonstrating a range of roughly 45 m with a limited rate of 7 bps.

III. SMART GLASS: DUAL-CELL LIQUID CRYSTAL SHUTTER

In this section, we give a brief background on LCDs and introduce the Dual-cell Liquid Crystal Shutter (DLS) as a smart glass technology for wireless communications applications [2]. Then, we describe the DLS-based sunlight communication system.

A. *Basics of Liquid Crystal Devices*

A single-cell LCD consists mainly of a Liquid Crystal (LC) layer placed between two polarizers and two glass substrates as depicted in Fig.2. The light polarization is the fundamental property on which the LCD's mechanism is based [2]. The incoming unpolarized light is filtered by the back polarizer (Polarizer 1), which permits the passage of the light component with polarization direction parallel to the polarizer's axis. Then, voltage levels applied at the LC layer varies the light polarization. At the front polarizer (Polarizer 2), two states are observable:

- Open or Clear state (maximum transmittance) where the light passes because its polarization direction is parallel to the axis of Polarizer 2.
- Close or Dark state (minimum transmittance) where the the light is blocked because its polarization direction is different than the axis of Polarizer 2.

The two states are also referred to as the ON and OFF states which indicates the existence and absence of an electrical field at the LC layer. Further, according to the relative angle between the axes of the two polarizers, two configurations of the LCD can be identified [2]. An LCD has a Normally White (NW), or a Normally Black (NB) configuration, if its polarizers are parallel or perpendicular, respectively. The configuration of the LCD determines how the clear/dark and

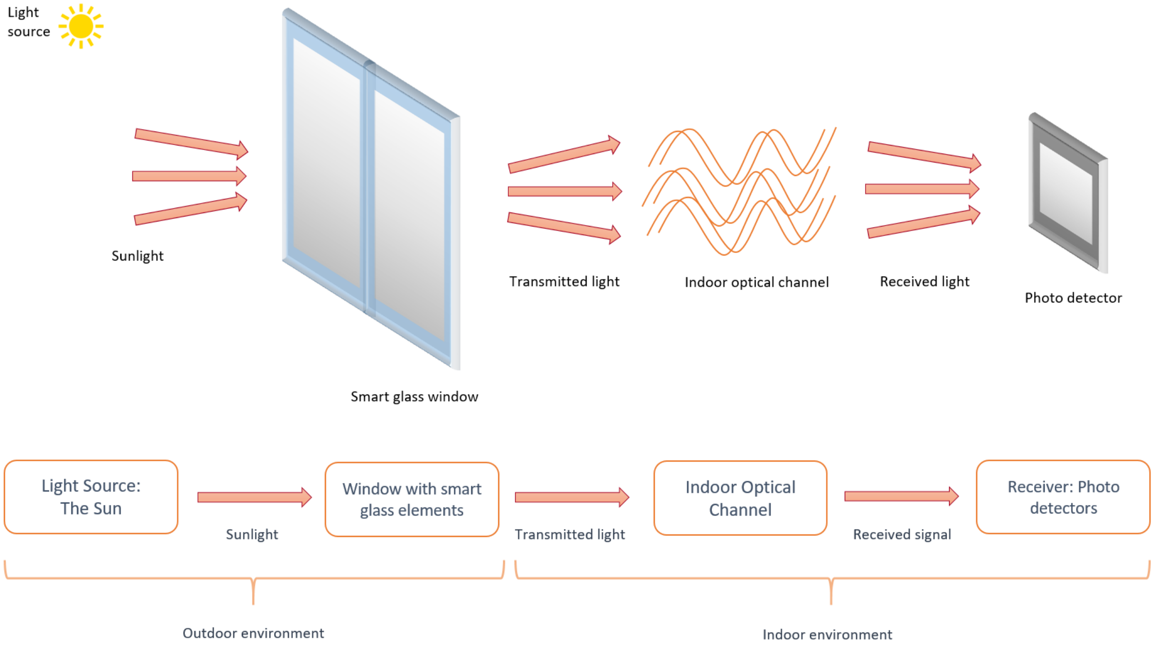

Fig. 1: General Overview of the Sunlight Communication System.

the ON/OFF states are mapped. For instance, clear and dark states represent the OFF and ON states of an LCD operating with NW configuration, and vice versa if LCD uses NB configuration. The switching time between the two states of the LCD is known as the opening time when the LCD switches from dark to clear states and the closing time when the LCD switches from clear to dark states. We note that the opening and closing times of a single-cell LCD are usually asymmetrical. Typically, an LCD with a NW configuration requires more time to open than to close, whereas the opposite is true for an LCD with NB operation.

B. *Design of Dual-cell Liquid Crystal Shutter*

To build our Dual-cell Liquid Crystal Shutter (DLS) [2], we stack two LC cells having opposite operations, using three polarizers, as shown in Fig. 2. LC Cell 1 is normally white having Polarizers 1 and 2, and LC Cell 2 has NB operation with Polarizers 2 and 3. To alleviate the flicker problem and to allow the use of a polarization-based modulation, Polarizer 3 is separated from the modulator side and placed at the receiver side. The DLS can transmit either a bit 0 or 1 by controlling each LC cell (LC Cell 1 and 2) separately. It applies distinct voltage levels to each cell simultaneously using a controller that generates the required. Now, focusing on DLS pixel 1 in Fig. 2, the polarized light emerging from the modulator side has a polarization angle $\phi_1 \in \{0°, 90°\}$. Once it reaches the receiver side, the light passes through Polarizer 3 with polarization angle $\theta_{31} = 0°$. Two cases can be observed:

- If bit 1 is transmitted, then ϕ_1 and θ_{31} would be equal giving a clear state.
- If bit 0 is sent, then ϕ_1 and θ_{31} would be different giving a dark state.

The dual-cell design offers the following benefits:

- Compared to single-cell LCDs, the DLS features fast and equal switching times. By leveraging the shorter times of each cell (opening and closing times of the NB and NW cells, respectively), the sum of the DLS's switching times is shorter compared to single-cell LCDs. Also, it resolves the switching times asymmetry issue by having NB and NW cells with equal times.
- When an array of DLS pixels is employed, the proposed design eliminates the inter-symbol interference. Indeed, because of the LC layer's properties, the DLS remains in an inactive state, for a specific duration T_{off} during which it cannot modulate the sunlight. Thanks to the dual-cell design, only negligible light transmission is allowed during T_{off} permitting other DLSs to send data without interference.
- The design mitigates the flickering problem and enables polarization-based modulation.

C. *DLS-based Sunlight Communication System*

We develop a sunlight communication system based on the proposed DLS design. The smart glass window is embedded with an array of DLSs which we refer to as the sunlight modulator. At the receiver side, two polarizers with distinct polarization axes, as shown in Fig.2, are attached to two photo detectors, in order to detect the received signal.

The array of DLS pairs that construct the sunlight modulator can be set up in several ways. Fig.3 presents one possible arrangement with two groups of 6 DLS pixels. Each group can send data over one polarization channel, and each pair of DLS pixels can transmit information over the two orthogonal polarization channels 1&2 simultaneously. In Fig.3, the pairs are identified by their indices, for instance the DLS pair $DLS_{1,1}$ and $DLS_{1,2}$ should send symbols during the same symbol duration T_{sym} over channel 1 and 2, respectively.

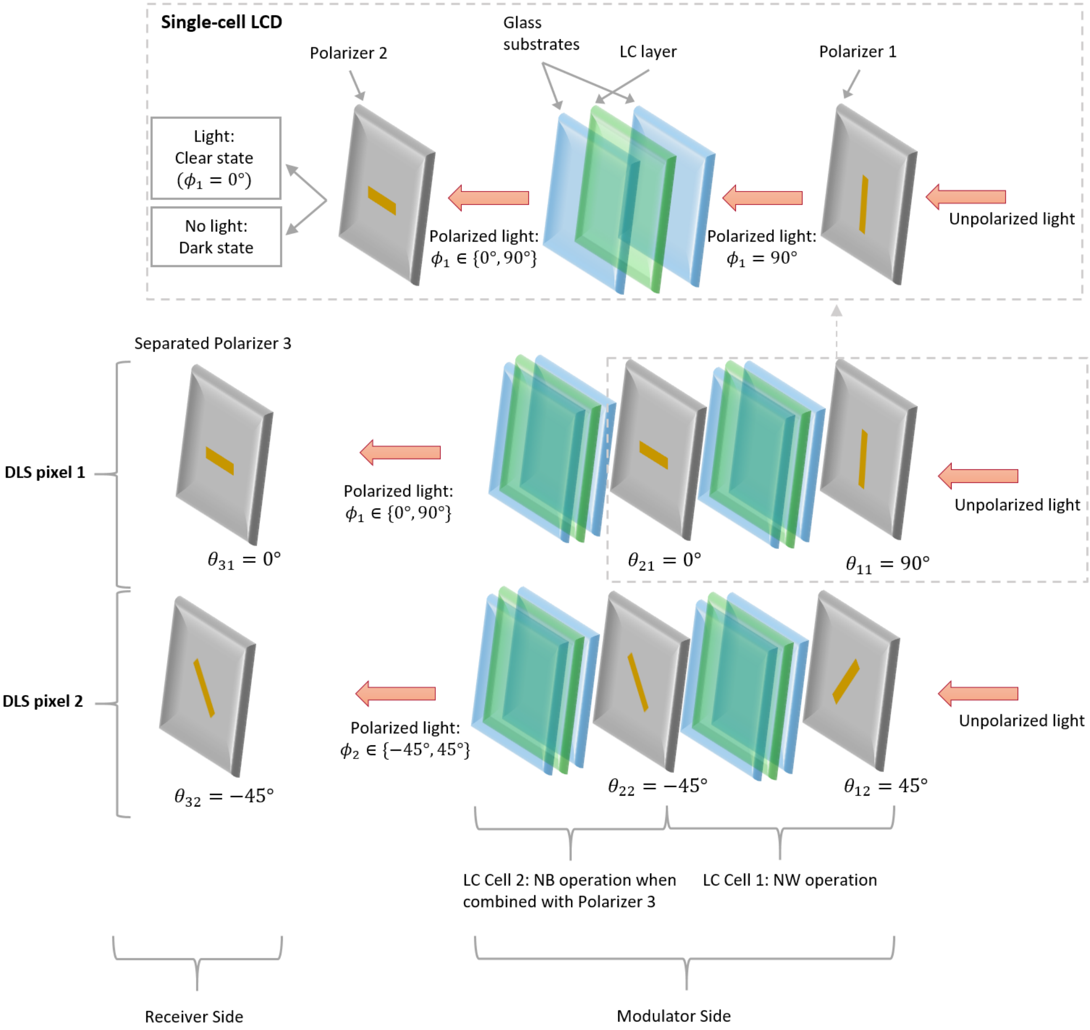

Fig. 2: Proposed Design of Dual-cell Liquid Crystal Shutter (DLS).

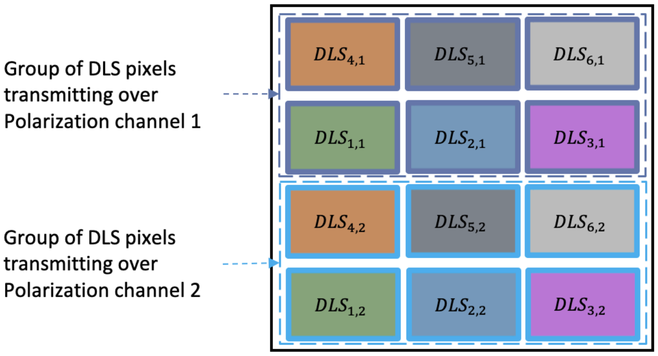

Fig. 3: Sunlight Modulator

After exploiting the polarization dimension through the DLS pairs, the modulator employs a Time Division Multiplexing (TDM) technique, using the two group of pixels, to profit from the time domain in order to boost the data rate.

1) Polarization-based Modulation: We take advantage of the polarization characteristic of sunlight to attain two objectives: flicker effect mitigation and data rate improvement. The polarization-based modulation scheme is based on the PQAM technique that was first proposed in [9], and it is enabled by the proposed design of the DLS pair. As illustrated in Fig.2, the polarizers axes of DLS pixel 1 and DLS pixel 2 have relative polarization angles equal 45°. In particular, the axis of Polarizer 1 in DLS pixel 1 makes a $\theta_{11} = 90°$ angle with respect to the horizontal direction, whereas it makes a $\theta_{12} = 45°$ angle in DLS pixel 2. Such relative angle results into the polarization channels orthogonality, which has been proven in [2], hence, the two pixels ability to operate simultaneously without interference.

After passing through the various layers of the DLS at the modulator side, the incident sunlight, characterized as unpolarized light, emerges as a polarized light. Its polarization angle, ϕ_1 in case of DLS pixel 1 and ϕ_2 in case of DLS pixel 2, can have two possible values which depend on the transmitted bit being either 0 or 1, as explained in Section III-B. Then, the light polarization is mapped into a light intensity because of the third polarizer's effect at the receiver side.

Multiple intensity levels can be produced establishing a L-PQAM scheme which would further boost the data rate. Practical implementation of such modulation would include the variation of the applied voltage on the DLS pixel or the use of different DLS areas to generate different intensity amplitudes.

2) Time Division Multiplexing: To exploit the time dimension for data rate enhancement, we use a Time Division Multiplexing (TDM) method demonstrated in Fig.4 using N DLS pixels, having 4 intensity levels.

Now, assuming that $N = 6$ and focusing on one group of DLS pixels in Fig.3, the total time frame T_{tot} is used by the 6 DLSs where each DLS transmits data during one time slot which is equal to T_{sym}. As mentioned in the previous section, a DLS, for example $DLS_{1,1}$, is in an *inactive state* for a certain period T_{off} after sending data. Thus, each DLS of the remaining pixels of the group ($DLS_{1,1}$, $DLS_{2,1}$, ..., $DLS_{6,1}$) can use one time slot of the inactive time T_{off} for data transmission until $DLS_{1,1}$ is able of sending data again.

The number of pixels necessary to utilize the total time frame is $N = \lfloor T_{\text{tot}}/T_{\text{sym}} \rfloor$ and it is doubled when the polarization dimension is exploited using the two orthogonal channels.

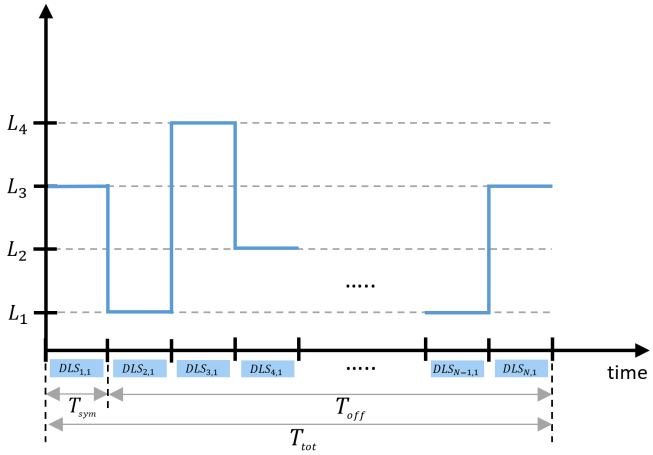

Fig. 4: Illustration of the Time Division Multiplexing (TDM) Technique

D. Performance Analysis

Because it provides a better understanding of the achievable rate, we study the overall throughput, defined as the rate of the successfully detected bits at the receiver, to comprehend the system's communication performance. The simulation results in Fig.5 show the variations of the throughput versus the link range, when 70 DLS pixels are used in the modulator to fully exploit the polarization and time domains. First, we can observe that the overall throughput gradually increases because more DLSs contribute to the system's throughput, since the growing distance between the modulator and the receiver allows the photodetectors to detect the data sent from more DLSs. Therefore, the highest throughput is attained, when the receiver is placed far enough to capture the sunlight, transmitted by all of the array's pixels. Then, the throughput starts to decline, after a particular distance, due to the low light intensity at longer distances caused by the wireless channel attenuation.

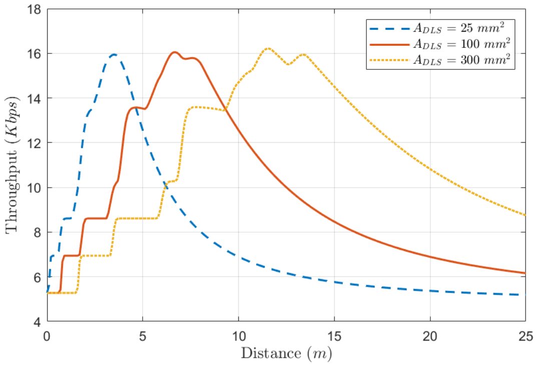

Fig. 5: Overall throughput versus link range for different DLS areas.

Moreover, increasing the DLS area extends the system's communication range where it achieves its maximum throughput at longer distances. For instance, if pixels with small areas $A_{\text{DLS}} = 25mm^2$ are used, the throughput is maximized at roughly 4 meters range. Meanwhile, if the DLSs areas are $A_{\text{DLS}} = 300mm^2$, the maximum of about 16 $Kbps$ is achieved at 11 meters. This is expected because larger DLS areas generate greater light intensities which can travel further in the indoor environment allowing the system to operate over extended link ranges.

Furthermore, we analyse the energy consumption of the proposed sunlight modulator based on the data available in [8]. We find that the total average power required for the operation of the modulator is 1 W, which can be fulfilled using a solar panel with a maximum power of 1 W, an open circuit voltage of 13 V and a short circuit current of 0.4 A.

We refer the reader to reference [2] where we provide further details on the proposed system in terms of design, mathematical modeling and simulation results, which were based on practical system parameters.

IV. SUNLIGHT COMMUNICATIONS: OPEN ISSUES

This section discusses various open issues in sunlight communications and suggests possible solutions. The main challenges of such passive communication systems include the selection of the modulating surfaces, the problems introduced by the passive characteristic of the link, such as the dependency of the sunlight intensity on multiple factors and the limited achievable data rate, and the difficulty of designing two-way communication links.

A. Choosing the modulating surfaces

Two types of modulating surfaces can be utilized in sunlight communication systems, namely transmissive surfaces (LCDs) and reflective surfaces (MEMS-based microshutters).

On one hand, the use of LCDs in such systems show promising results. Leveraging the LC layer's properties such as the ability to control light polarization enabled polarization-based modulation techniques and flicker-free communications. Nonetheless, having switching times with tens of μs order, limits the achievable data rate to tens of $Kbps$ at most. Thus, LCDs switching times optimisation is needed to reach higher data rates. Moreover, the light intensity attenuation, caused by the propagation through the LCD layers, restricts the link range to few tens of meters. This can be solved by focusing the sunlight to increase its intensity, without damaging the LCD. Besides, intelligent surfaces can be integrated with standard LCDs or the proposed DLS design offering further system flexibility and performing functionalities like light focusing, reflecting, and spreading to provide multiple-access coverage.

On the other hand, MEMS-based microshutters feature switching times that can be shorter or similar to LCDs (few to tens μs), providing flicker-free communications. Indeed, the flickering problem is eliminated if the frequency of light intensity variations is higher than 200 Hz [5], equivalently the switching time is shorter than 5 ms. However, microshutters can cause visual discomfort [4] and have low flexibility, compared to LCDs, restricting light modulation to intensity modulation.

Furthermore, other materials, such as meta-surfaces, may be employed as modulating surfaces for sunlight communications and investigation of their potential use for such application is necessary.

B. Dealing with practical considerations

To enable practical applications, several issues should be handled. First, the main limitation of sunlight communications is the dependency of the solar irradiance on the location, the time of the day and the weather conditions. This can result in links unreliability which can be addressed by focusing the sunlight on the LCD area [5].

Additionally, sunlight communication systems are usually based on point to point links. Indeed, the pointing and tracking between the transceiver ends is a challenging task in OWC. Particularly, the receiver's mobility and orientation can affect the links reliability especially for systems adopting polarization-based modulation techniques requiring precise pointing between the modulator and the receiver. PIXEL [14] and RetroTurbo [9] address the angular misalignment between the transmitter and receiver by adding a dispersor after the LC layer at the transmitter side, and by using conventional correction methods for QAM constellation rotation, respectively. Our proposed system can adopt similar solution as RetroTurbo.

Moreover, assuming the scenario described in Section II where the indoor area is fully illuminated by the sunlight and artificial light is minimized to save energy, an interference can occur between the modulated light emerging from the smart glass elements and other sun rays coming from other parts of the window. Such issue can be mitigated by covering the entire window area with smart glass elements, however, further investigations are necessary to address such open issue.

C. Boosting the data rate

The state-of-the-art of sunlight communication systems can achieve maximum data rates of few tens of $Kbps$. Even though it is sufficient for indoor Internet of Things (IoT) sensor applications, additional improvements in the communication performance of such systems are necessary to target a variety of applications. Boosting the data rate is difficult because of the passive aspect of the sunlight communication link and the limited levels of flexibility provided by the smart glass devices. Nonetheless, data rate enhancements can be realized by optimizing the switching capabilities of smart glass technologies, or by developing more sophisticated modulation techniques that can exploit the different properties of light including the intensity, polarization and wavelength.

D. Developing two-way communication links

Sunlight communication systems are based on the natural flow of sun rays from one milieu to another in a one direction manner, creating a one-way passive communication link. Hence, to establish a fully passive two-way link, sunlight needs to be properly redirected. This is possible through backscatter communications where the receiver side can be equipped with a refelctive surface redirecting the light back to the transmitter side. In this case, each link end would have two components: a transmitter and a receiver.

V. CONCLUSION

In this article, we explored sunlight communication systems and highlighted the issues that arise with their development while presenting possible solutions. Moreover, we proposed a new smart glass device based on LCDs, using which we build our sunlight communication system that exploits the time and polarization domains to enhance the data rate. To summarize, sunlight communications is a promising alternative for wireless communication technologies, however, further research efforts are required to tackle the various challenges.

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